Appendix D

USAERDC Groundwater Model

Northwest Boundary Area RCRA Facility Investigation
Fort Buchanan, Puerto Rico

APPENDIX D. GROUNDWATER FLOW AND TRANSPORT MODELS

Groundwater flow and transport models were constructed to simulate the subsurface conditions at Fort Buchanan in support of the Northwest Boundary Investigation. This appendix describes the approaches, input parameters, results and conclusions used in or derived from this modeling effort. The effort was carried out by the Hydrologic Systems Branch of the Coastal & Hydraulics Laboratory at the US Army Engineer Research & Development Center (ERDC) in Vicksburg, MS. In addition, Mr. Charlie Whitten, recently retired from the Geotechnical & Structures Laboratory at ERDC, was instrumental in supporting this modeling effort.

D.1 SUBSURFACE HYDROGEOLOGIC SETTING

The subsurface hydrogeologic conditions of the model are identical to those described in detail in Section 2. In order to facilitate the construction of a three-dimensional (3D) numerical model of the groundwater flow system at the site, a geologic conceptual model was constructed using all available subsurface data. Soil borings from on-site monitoring well installations as well as those made available from the neighboring Caribbean Petroleum Refinery (CPR) to the west were used, along with the documented regional geologic setting for the site, to construct a 3D representation of the subsurface geology of the near-surface aquifer system at Fort. Buchanan. Figure D-1 depicts the locations of the 45 boreholes used in the construction of the geologic conceptual model. Figure D-2 depicts these same boreholes as seen from an oblique angle with the vertical dimension exaggerated by a factor of 7. The color-coded segments of the boreholes correspond to the various soil layers of the stratigraphy as indicated by the legend.

Using the boreholes and an understanding of the geologic setting of the site, borehole cross sections were defined between boreholes to further delineate the configuration of the subsurface stratigraphy across the model study area. A 3D geologic conceptual model (or “solids model”), shown in Figure D-3, was constructed from the boreholes and borehole cross sections using the “horizon’s method” in the Department of Defense Groundwater Modeling System (GMS). The cross sections depicted in Figures 2-5 through 2-9 of Section 2 were created by making vertical cuts of the solids in Figure D-3 at the locations indicated in Figure 2-4.

A 3D model such as shown in Figure D-3 is very useful in gaining a more complete understanding of the subsurface flow system at a site such as Fort Buchanan. The dualzone nature of the aquifer system is evident by examining the cross sections of Figures 2-5 through 2-9. The figures show the older terrace carbonate sand and silt layers (labeled with "OT" in the material legend and shown in darker colors) dipping to the north and, in the brief transition zone, being overlain by the younger terrace layers (shown in bright colors). The furthest south the younger terrace materials are found is just south of the source area near wells MW-PR-25 and MW-PR-14. To the east and west of this area the older terrace materials extend further north. However, in all areas the zone of overlap between the older and younger terrace materials appears to be relatively narrow. Figure D-4 depicts only the carbonate sand units of both the older and younger terrace units from an oblique angle where the narrow overlap zone of the units is clearly visible.

Because a generally impervious overburden clay material of varying thickness covers both the older and younger terrace layers throughout the study area, the ability of water to move from the older to younger terrace materials is an important hydrogeologic issue at the site. The transducer data plots found in Figure D-5 show the different responses that wells across the site have to various external forcings such as rainfall and tides. For example, included with the transducer data plots is a rainfall hyetograph for the January 2008 recording period in which a significant rainfall event was recorded on January 22 (Figure 5d). An immediate and sharp rise in groundwater level is noted in older terrace wells such as MW--09A (Figure D-5a) and MW-PR-19A (Figure D-5d). This would indicate that the older terrace unit in which these two wells are screened, CS1-OT, is recharged directly by rainfall somewhere south of the southern boundary of the model in the higher elevation areas where the overburden clay is no longer found at the surface. Deeper older terrace wells such as MW-PR-09B (Figure D-5a) and MW-PR-19B (Figure D-5d) also show a response to rainfall but one that is slightly less sharp and immediate. However, wells that are screened in younger terrace materials, such as MW-PR-07A (Figure D-5a) and MW-PR-13B (Figure D-5c), show a much less dramatic and lagged response to the January 22 rainfall event. What the transducer data plots from these younger terrace wells do show is a strong response to tidal forcings, presumably from contact with the tidal waters of San Juan Bay somewhere beyond the northern boundary of the model. Wells that are located in the transition zones between the older and younger terrace units, such as MW-PR-14A and MW-PR-14B (Figure D-5c), show a somewhat muted response to both the rainfall and tidal forcings. The transducer data results indicate that while there is communication of water between the older and younger terrace units in the study area, this communication is somewhat poor. The borehole and cross section data used to construct the 3D geologic conceptual model of the site does show areas of direct contact between the older and younger terrace units in the narrow zone of transition. However, these transitions often occur with younger terrace units overlying older terrace units, requiring that flows be communicated vertically – generally the flow direction with the lowest hydraulic conductivity in a fluvial depositional environment. The 3D solids model of the Fort Buchanan site appears to corroborate the conclusions that can be drawn from the transducer data – that there is communication of groundwater flow between the older and younger terrace units – but this communication is poor, resulting in lagged, damped response to external forcings from rainfall and tides beyond the southern and northern boundaries of the study area, respectively. Additional transducer data from selected wells (including the newer off-post wells OP-1, OP-5, OP-6 and OP-7) over the period of February 18 through March 11, 2009 is found in Appendix D and confirms the conclusions drawn from the data in Figure D-5. A rainfall event was recorded on February 27 and an immediate response is noted in well MW-PR-19A but the young terrace wells show very mild and lagged response to this rainfall event. Additionally, the tidal signature in the young terrace wells grows in magnitude with wells that are located further to the north.

D.2 NUMERICAL MODEL HYDROGEOLOGIC PARAMETERS

In order to determine hydraulic conductivity values for use in the numerical simulation of the groundwater flow system at Fort Buchanan, over 50 slug tests were performed at the 41 on-post monitoring wells as well as at the off-post monitoring wells OP-1 thru OP-7 as described in the Northwest Boundary Investigation report. From these slug tests, ranges of hydraulic conductivity values were estimated for the various geologic units of the Fort Buchanan Northwest Boundary groundwater flow system. These ranges were then used to select initial values in the model calibration process that will be described in Section D.4. The ranges for each geologic unit are shown in Table D-1.

The locations of boundaries for the numerical model were chosen based on available data and hydrogeologic conditions (see Figure D-6). The east and west boundaries were selected to lie along groundwater flow lines from the south to the north such that no flow would be expected to pass through the boundaries but rather flow along them in a “slip flow” fashion. These boundaries were estimated based on topographic data as well interpolations of water level data collected at the installation monitoring wells.

The northern, downstream boundary of the model was chosen to coincide with the edge of a small body of water approximately 600 feet to the north-northwest of OP-6. It is unknown if this body of water is in direct contact with the carbonate sand aquifers of the younger terrace materials (CS1 and CS2) as it may not fully penetrate the overburden material; therefore, estimated values of specified head were assigned to this downstream boundary based on the observed head values recorded from the transducers in OP-6 and OP-7. These downstream head values ranged from a low value of 3.25 feet on the northeast corner to 3.5 feet on the northwest corner. Specific values along the boundary between the two corners varied linearly with distance.

Table D-1. Slug Test Hydraulic Conductivity Ranges and Initial Model Values

Geologic Unit	Hydraulic Conductivity Range (ft/d)	Initial Value (ft/d)	Anisotropy Factor (horizontal:vertical)
Overburden	0.015 – 0.5	0.149	100
Channel Fill	0.2 – 20	10	5
Upper Carbonate Sand Aquifer, Young Terrace (CS1)	1.0 – 85	25	10
Lower Carbonate Sand Aquifer, Young Terrace (CS2)	1.0 – 90	50	10
Carbonate Silt, Young Terrace (CS)	0.0045 – 0.5	0.45	10
Upper Carbonate Sand Aquifer, Old Terrace (CS1-OT)	0.1 – 30	10	10
Middle Carbonate Sand Aquifer, Old Terrace (CS2-OT)	0.1 – 20	7	10
Lower Carbonate Sand Aquifer, Old Terrace (CS3-OT)	0.05 – 20	5	10
Carbonate Silt, Old Terrace (CS-OT)	0.001 – 0.05	0.04	10

The southern, upstream boundary of the model was chosen to coincide with Chrisman Road, which represents the southernmost extent of the monitoring wells that were drilled at the site and which also encompasses CEMEX Lake. Specified head boundary conditions were also assigned to this upstream boundary condition using the observed head values from the nearby monitoring wells. All three older terrace aquifer units are present along the upstream southern boundary and observed head data indicate that the lower units are at successively higher pressures. Thus, higher head values were assigned to the lowest aquifer unit (CS3-OT) with progressively lower head values assigned to the middle (CS2-OT) and upper (CS1-OT) aquifer units. The assigned head values ranged from 35-40 feet on the southwest corner to 33-38 feet on the southeast corner. These upstream boundary condition values were modified during the calibration phase as described in Section D.4.

As indicated in the previous section, a relatively impermeable layer of overburden material that thickens from south to north overlies the entire study area. This overburden material effectively prevents any direct recharge of the underlying carbonate sediment aquifers through infiltration of rainfall within the boundaries of the study area. As discussed previously, the older terrace aquifer units are recharged in the higher elevations to the south of the southern boundary of the study area where the overburden material is not present. The younger terrace units are not directly recharged from the surface but instead receive flow through subsurface contact with the older terrace units in the transition areas discussed previously. Accordingly, no recharge was specified to the overburden materials at the surface in the groundwater model simulations.

D.3 NUMERICAL FLOW MODEL APPLICATION

The numerical modeling code selected to simulate the groundwater flow system at the Northwest Boundary of Fort Buchanan is MODFLOW2000, a widely used finite difference groundwater flow code developed by the USGS (Harbaugh et al., 2000). The code is limited to simulation of saturated zone flow only, but given that no infiltration is being simulated in the Fort Buchanan model, this limitation will have no impact on the simulation results. Figure D-7 depicts the finite difference grid used to carry out the simulations of the groundwater flow system at Fort Buchanan. The grid cells are color-shaded to correspond to the soil material type assigned to the cells, according to the solids model shown in Figure D-3. Soil hydraulic conductivities associated with each material type from Table D-1 are also assigned to each cell based on their assigned material.

Groundwater flow in the Fort Buchanan aquifers was simulated in steady-state rather than transient fashion. Transducer data from wells screened in the younger terrace units did provide sufficient data from which a transient tidal signal could have been synthesized for boundary conditions along the northern boundary of the model. However, given that the purpose of the model was to simulate the long-term flow patterns in the aquifer system at the site and use those flow patterns to determine the long-term migration of subsurface contaminants, the daily variations in head due to tidal influences are insignificant and do not affect the long-term flow patterns of the system.

D.4 NUMERICAL FLOW MODEL CALIBRATION AND RESULTS

Using the hydrogeologic parameters of hydraulic conductivity and the values estimated as specified head values on the northern and southern boundaries of the flow model, model simulation results were compared with observed head values in the installation monitoring wells. Because the model results were steady-state conditions and the installation wells were observed in transient conditions, long-term average values were estimated for the 32 observation wells and used in the model calibration process. Hydraulic conductivity and boundary condition values were adjusted throughout the calibration process, using the range of values listed in Table D-1 as bounds for each hydraulic conductivity parameter and reasonable limits for the boundary condition values.

Table D-2. Calibrated Hydraulic Conductivity Values for Soil Material Types in Model

Geologic Unit	Calibrated Hydraulic Conductivity Value (ft/d)	Calibrated Anisotropy Factor (horizontal:vertical)
Overburden	0.015	100
Channel Fill	1	5
Upper Carbonate Sand Aquifer, Young Terrace (CS1)	40	10
Lower Carbonate Sand Aquifer, Young Terrace (CS2)	40	10
Carbonate Silt, Young Terrace (CS)	0.045	100
Upper Carbonate Sand Aquifer, Old Terrace (CS1-OT)	0.25	10
Middle Carbonate Sand Aquifer, Old Terrace (CS2-OT)	0.25	10
Lower Carbonate Sand Aquifer, Old Terrace (CS3-OT)	0.1	10
Carbonate Silt, Old Terrace (CS-OT)	0.005	100

Table D-3. Calibrated Boundary Condition Values on Northern and Southern Boundaries

Location and Unit	Boundary Condition Value (feet)
Northwest Corner – both CS1 & CS2	3.5
Northeast Corner – both CS1 & CS2	3.25
Southwest Corner – CS1-OT	35
Southwest Corner – CS2-OT	39
Southwest Corner – CS3-OT	40
Southeast Corner – CS1-OT	33
Southeast Corner – CS2-OT	37
Southeast Corner – CS3-OT	38

Table D-2 lists the calibrated hydraulic conductivity values for each soil material type and Table D-3 lists the calibrated boundary condition values. Due to the vagaries of subsurface water level measurement and local variations in stratigraphy, it is unlikely that a flow model can ever be calibrated precisely to a given set of observed water level elevations. Rather, accepted practice in calibration of groundwater models is to determine an acceptable level of calibration error, as measured using the metrics of mean error (ME), mean absolute error (MAE), and root-mean-square error (RMSE), and then adjust the parameters of the model about which there is uncertainty until the error metrics are as low as possible and also below the acceptable level of error. ME is computed by:

$$ME = \frac{1}{n}\sum_{i=1}^{n}(f_i - y_i)$$

where f_i is the observed water level value, y_i is the model-computed water level value and n is the total number of observed values. MAE is computed by:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}| f_i - y_i |$$

and RMSE is computed by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(f_i - y_i)^2}{n}}$$

RMSE is generally considered to be the most conservative error metric since it is weighted to give emphasis to large errors. RMSE is the metric used in this model study to determine the level of calibration as described below.

The target acceptable level of calibration error for groundwater models is often chosen to be 10% or less of the maximum head difference between the high and low groundwater head values in the model. In the Fort Buchanan model, the highest head values were between 35-40 feet and the lowest values between 3.25-3.5 feet. Thus a target acceptable level of error of 3.15 feet was chosen for the ME, MAE and RSME metrics of the minimum acceptable level of calibration. The final calibration metrics for the values listed in Tables D-2 and D-3 are presented in Table D-4.

Table D-4. Final Model Calibration Error Metrics

Calibration Metric	Calibrated Value (feet)
ME	0.313
MAE	1.142
RMSE	2.169

In addition to achieving a calibration metric that is below the target acceptable maximum, the spatial distribution of the error values is an important component of determining model calibration. Ideally large and small error values should not all be clustered or grouped on a particular portion of the model but rather distributed evenly across the model domain. Figure D-8 depicts error bar indicators, using the RSME metric, at the 32 calibration targets of the Fort Buchanan model for the model result corresponding to the calibrated input parameters listed in Tables D-2 and D-3. Green bars indicate less than 1.0 feet difference in water level value between the observed and computed head, yellow bars represent between 1.0 and 2.0 feet difference and red bars indicate greater than 2.0 feet difference. The direction of the bars (above or below the black horizontal center bar) indicates whether the computed value is greater than or less than the observed value, respectively.

As shown in Figure D-8, there is very good agreement between the model and observed values in the northern end of the model while the largest errors exist in the higher elevations at the southern end. However, it should also be noted that in the northern low elevations, there is very little difference in the water levels in this area and thus the magnitude of the errors is very small compared to the upland areas in the south. Additionally, there is less confidence in the geologic conceptual model at the southern end given the fact that fewer boreholes were drilled in this area. The Northwest Boundary Investigation concentrated on the area in and around the suspected contamination source near MW- 26 and areas downstream. Since no hydrocarbon contamination has been detected in any monitoring well upstream of these areas, little effort was expended on further defining the geology in this area. It is therefore not surprising that wells in this area have larger RMSE error value given that there are possible discrepancies between the geologic conceptual model and the actual aquifer system in this area. However, overall, the errors are well within the target range and are also fairly evenly distributed across this portion of the model, thus the calibration of the model is deemed to be sufficient for the purposes of this study. Additionally, the calibration of the water levels in the suspected source area and downstream areas is excellent, which affords a high degree of confidence in the model's ability to simulate the aquifer groundwater flow conditions in these areas.

One of the main purposes in developing the groundwater flow model of the Fort Buchanan Northwest Boundary area was to determine the groundwater flow velocities along the length of the contaminant plume as it migrates in a north-northwest direction towards the off-post wells (OP-1 through OP-7). Figure D-9 shows contours of the magnitude of the groundwater flow velocities as computed by the model at a depth corresponding to the greatest flow velocities in the CS2 aquifer. The model results indicate that the greatest flow velocities along the length of the plume are as high as 10 ft/d in some small pockets, mainly near the source area. In general, however, the flow velocities are generally in the range of 3-6 ft/d, and at the downstream end of the plume, near wells OP-6 and OP-7, flow velocities are in the range of 2-5 ft/d. A conservative estimate for flow velocity along the length of the plume would therefore be in the range of 6-7 ft/d.

D.5 ANALYTICAL TRANSPORT MODEL RESULTS

Using the flow velocities computed by the flow model, a transport model was used to simulate the advection and dispersion of the dissolved contaminants in the aquifer downstream of OP-6. The simulations were carried out in the area from OP-6 northward to the northern boundary of the groundwater model, coinciding with the surface water body located approximately 600 ft to the north of OP-6. While it is unlikely that this lagoon fully penetrates the thick overburden material and comes into direct contact with the uppermost units of the carbonate sand aquifer, for conservative purposes it was assumed that this northern boundary represented the potential contact point between any dissolved contaminants in the groundwater and a surface water body.

The analytical transport model ART3D (Clement, 2001) was used to carry out these transport simulations. An analytical model, while not as rigorous as other 3D transport modeling codes, is able to provide sufficient physical process simulation to address the relevant issues at the Fort Buchanan site. Given the long period of time that has likely past since the contaminants first were introduced to the aquifer system, the unknown quantity of contaminant and the exact nature of it, and the relatively short period of monitoring data available for the plume extent and concentrations over time, successful application of a more detailed and rigorous 3D transport model is highly unlikely. The results of any such application, if successful, would also be highly suspect given the large number of assumptions and extrapolations that would necessarily be made in order to obtain model results. For these reasons it was determined that an analytical model with few assumed parameters would be the most appropriate choice for application at the Fort Buchanan site.

The ART3D analytical model assumes a steady flow field in a uniform direction with a source concentration of a specified size in width and depth at one end of a rectangular model domain. The user specifies the flow velocity, the input concentration, the width and depth of the plume, a retardation coefficient, the longitudinal dispersion coefficient, transverse and vertical dispersion ratios, and the decay constant for the contaminant. The transport calculations are then carried out over a user-specified period of time with concentrations being computed at set intervals throughout the model domain.

As discussed in Section 5, the surface water body located to the north of OP-6 and OP-7 was determined to be the only possible receptor of contaminated groundwater that had the potential for exposure to biota. The direct connection of groundwater to this surface water body is unlikely as the overburden material is greater than 40 feet thick in this area. Additionally, the CP1 and CP2 aquifers are dipping to the north. However, in order to ensure a conservative assessment of potential contamination transmission pathways, it is assumed that the levels of contamination currently observed at OP-6 will have a direct pathway to the surface water body to the north of OP-6 and that the pathway will allow the contaminated ground water to enter the surface water body at the southern edge, approximately 600 feet from OP-6 (see Figure D-10). Additionally, it is also assumed that the inevitable dissolution of any contaminated groundwater will not occur, but instead the potential receptor organism will be exposed to the contaminated groundwater without any mixing with surface water.

Conservative assumptions of transport parameters for trichloroethylene (TCE) were selected for use in the ART3D simulations in this fashion: The width and depth of the plume were assumed to be 100 and 40 feet, respectively. The retardation coefficient was assumed to be 1.1 and the longitudinal dispersion coefficient was chosen as 16.8 with transverse and vertical ratios of 0.2 and 0.01, respectively. The TCE decay constant was selected to be 0.000534. These values were all selected based on conservative estimates of TCE plumes of similar age and in similar geochemical conditions. The groundwater flow velocity was estimated to be 6.5 ft/d as based on the flow model results.

Simulations were conducted using the transport model to determine what the concentrations of contaminants 600 ft downstream from OP-6 might be given various scenarios. Using the maximum observed value at OP-6 of about 140 µg/L, the transport simulations indicated a maximum concentration of less than 75 µg/L at the southern boundary of the surface water body (see Figure D-11). As an exercise to determine the sensitivity of the model results to the groundwater flow velocity, the velocities were increased to 650 ft/d, a value 10 times greater than those computed by the flow model. The resulting simulation increased the downstream concentration to approximately 80 µg/L, an increase of around 5 µg/L.

The transport model was then used to determine the minimum concentration needed at OP-6 to achieve a concentration of 350 µg/L at the southern boundary of the surface water body. As indicated in Section 5.4, 350 µg/L represents the ECOTOX threshold value established for surface water screening of TCE (EPA, 1996). According to the transport model results, a concentration of approximately 675 µg/L would be required at OP-6 in order to exceed the 350 µg/L ECOTOX limit at the surface water body's southern boundary. Therefore, in order for there to be a concentration level that would exceed the ECOTOX limit in the surface water body, concentrations of approximately 650 µg/L would need to be detected at OP-6.

D.6 CONCLUSIONS AND RECOMMENDATIONS

In support of the Northwest Boundary Investigation of the Fort Buchanan RCRA Facility Investigation, a 3D geologic conceptual model was constructed based on site investigation data collected during the investigation and from existing external sources. This model was then used to build a 3D groundwater flow model that was used to simulate the groundwater flow system in the near-surface aquifers in the Northwest Boundary area of the installation where a TCE plume exists. The purpose of the modeling exercise is to better understand the surface flow system at the site and determine what the fate and transport characteristics of the plume might be in order that a viable remediation alternative can be selected.

In the construction of the geologic conceptual model it was determined that the Fort Buchanan aquifer system consists of two terraces: an older terrace that exists in the southern, higher elevations of the installation, dipping to the north; and a younger terrace that overlies the older terrace deposits where they overlap and is found in the lower elevation areas along the northwest boundary of the installation. In the study area, both aquifers are overlain by overburden material of very low permeability that effectively prevents infiltration of surface water, as verified by transducer and slug test data. The older terrace materials are recharged by infiltration in the higher elevation areas to the south while the younger terrace materials are recharged by water flowing from the older terrace units in the relatively narrow zone where the two aquifers overlap. The communication of flow between the two aquifers does permit some transfer of forcings such as increased water levels due to rainfall events, but the transfer is somewhat lagged and damped. The younger terrace materials experience tidal fluctuations and are evidently in contact with tidally influenced water sources beyond the northern boundary of the study area. These tidal influences are not transmitted upstream to the older terrace units.

Using the 3D geologic model, a 3D groundwater flow model was constructed and simulations carried out using the USGS code MODFLOW2000. The groundwater flow model was parameterized from slug test and other subsurface data and calibrated to observed water levels to determine the nature of the overall flow system in this portion of the installation. The model was calibrated to observed average head values from which a conservative estimate of groundwater flow velocity was obtained along the length of the contaminant plume. This groundwater velocity estimate was then used to determine the possible exposure concentrations of TCE in a nearby surface water body using very conservative assumptions regarding the possible exposure pathways for contaminants in groundwater at this site. The analytical transport model ART3D was used to carry out these simulations using conservative transport parameters. The resulting transport simulations indicated that using the current levels of observed contaminant concentration in OP-6 and OP-7, the wells closest to the surface water body, the expected levels of contamination to reach the surface water body are approximately 5 times lower than the EPA ECOTOX limit for TCE surface water contamination.

Given the results of the flow and transport models and the very conservative assumptions regarding the possible exposure pathways for the contaminated groundwater to reach the surface water body, it is recommended that a system of regular monitoring be implemented to determine if TCE concentrations that exceed 500 µg/L are recorded at OP-6 and OP-7. If rising concentrations approaching this level are observed, then alternative remediation techniques should be considered. However, as discussed in Section 5.6, given the reducing conditions and daughter products of TCE dechlorinization that have been observed at the site in the areas in and around the contaminant plume, it is unlikely that concentrations at OP-6 and OP-7 will approach the threshold value for concern and a system of monitored natural attenuation will be sufficient for this site.

D.7 REFERENCES

Clement, T.P., 2001. Generalized Solution to Multispecies Transport Equations Coupled with a First-Order Reaction Network, *Water Resources Research*, 37(1), 157-163.

EPA, 1996. *ECO Update, Ecotox Thresholds.* EPA-540/F-95/038.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00–0092, 121 p.

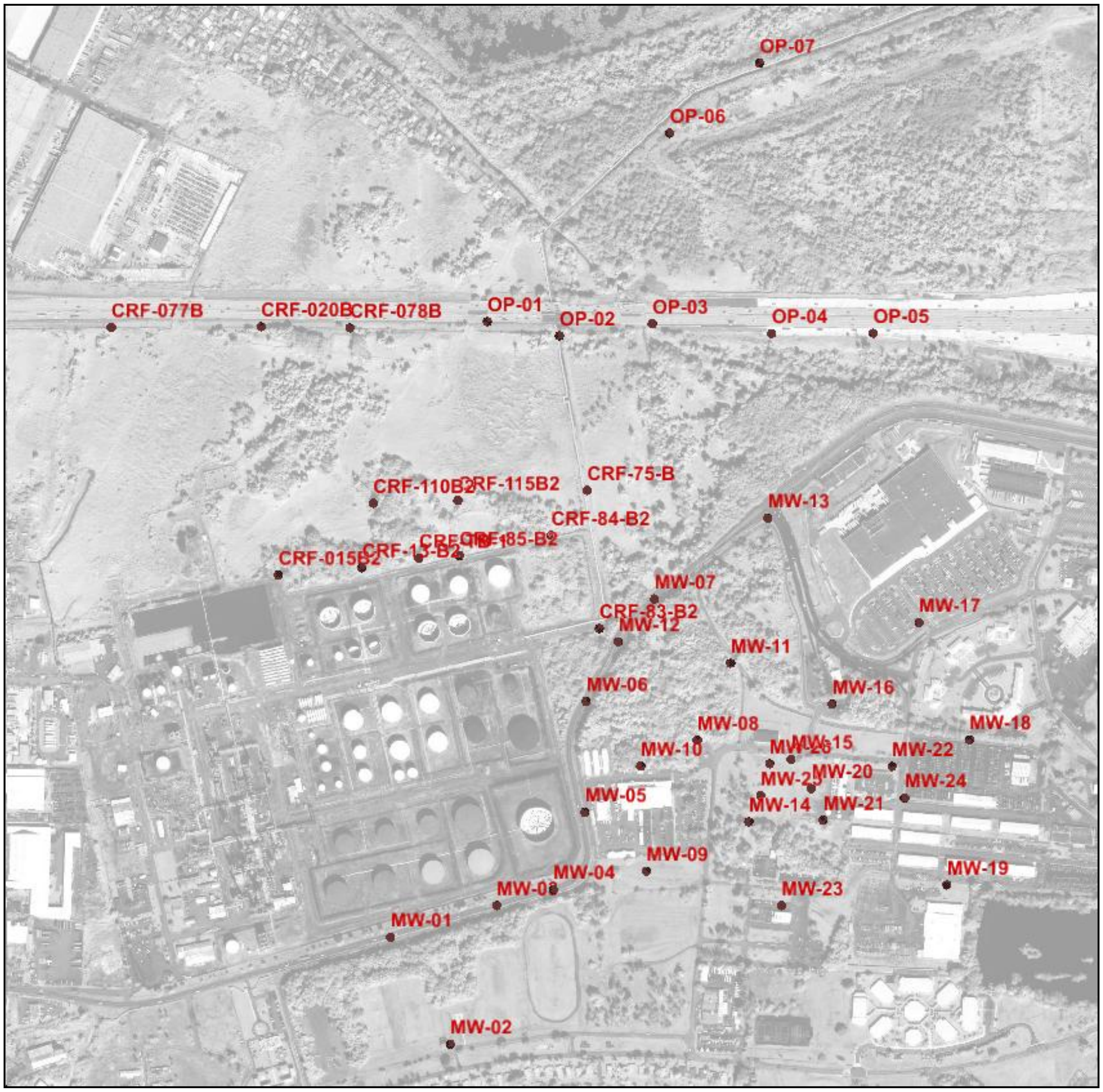

Figure D-1. Location of 45 boreholes from which geologic conceptual model was built.

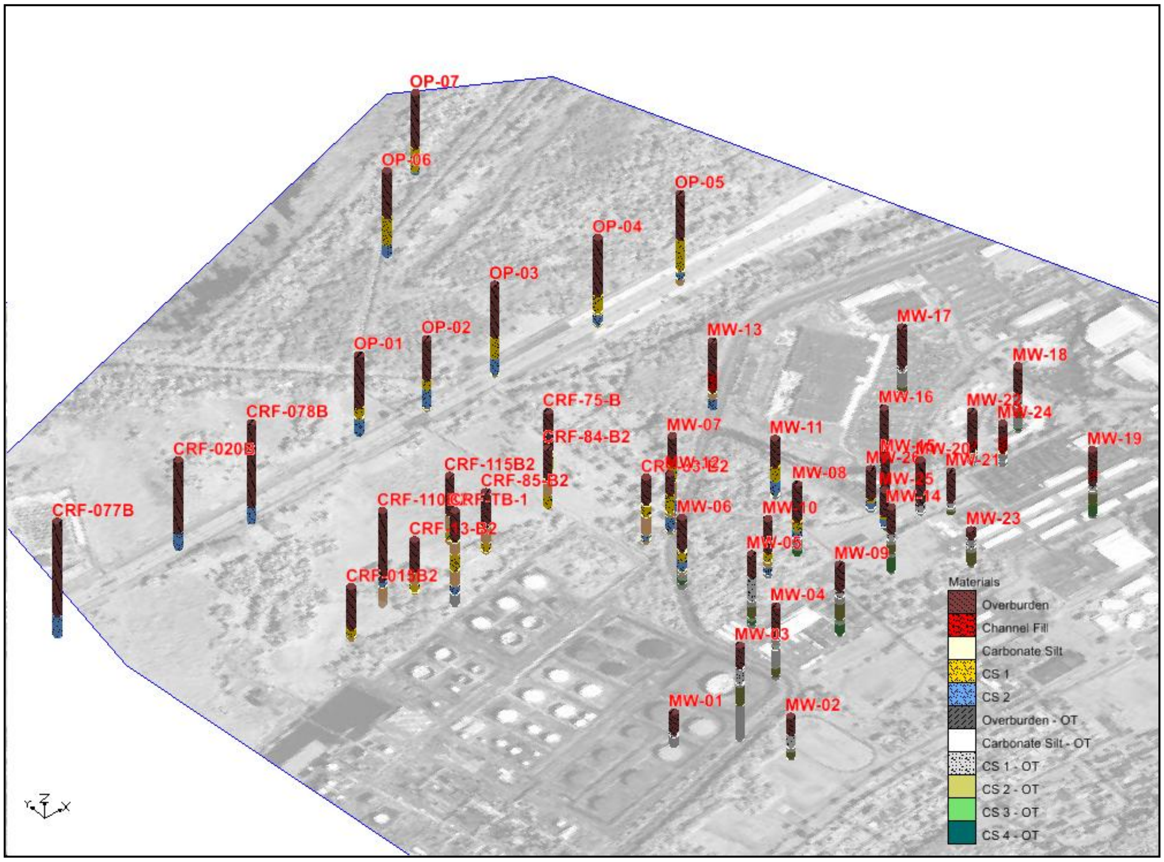

Figure D-2. Oblique view of boreholes with areal image displayed below boreholes.

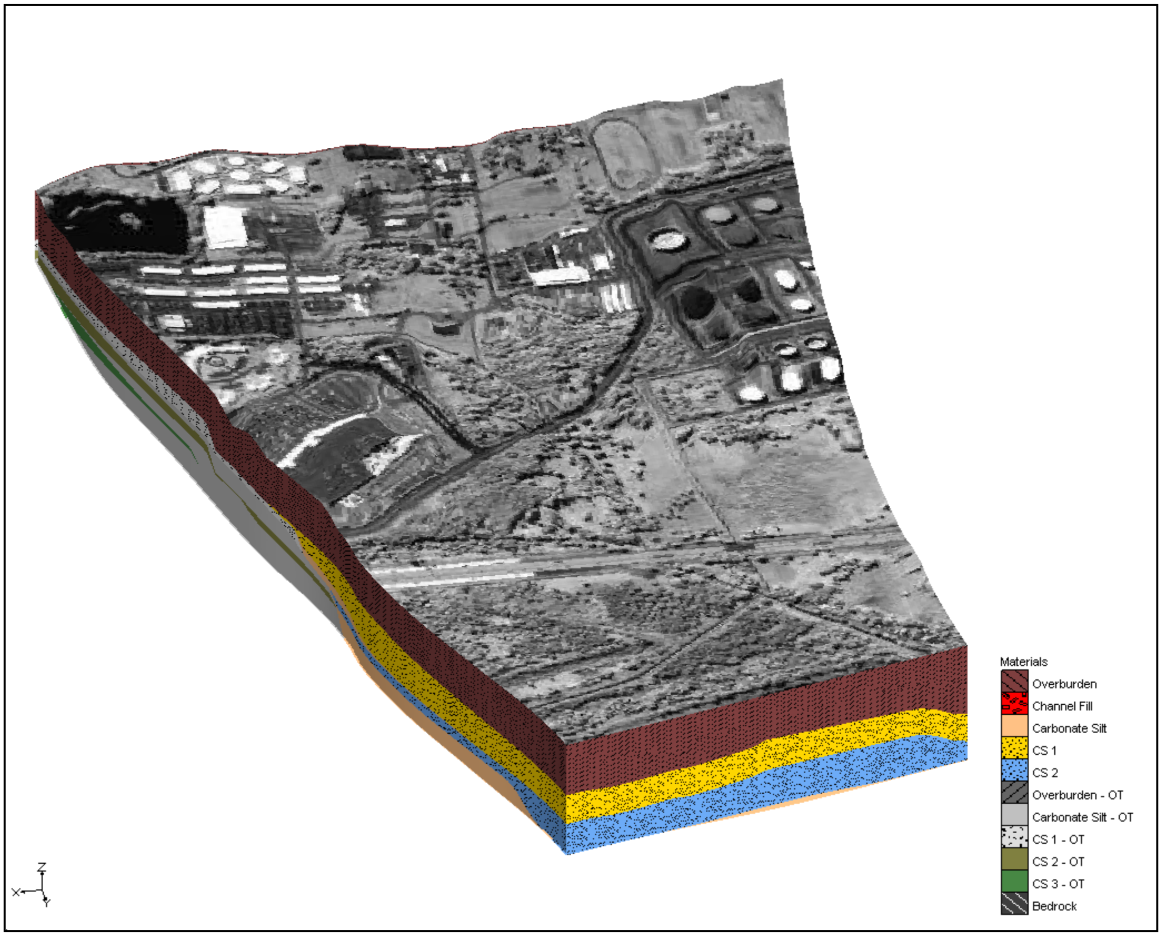

Figure D-3. Oblique view of 3D solids that comprise the Fort Buchanan Northwest Boundary Investigation geologic conceptual model.

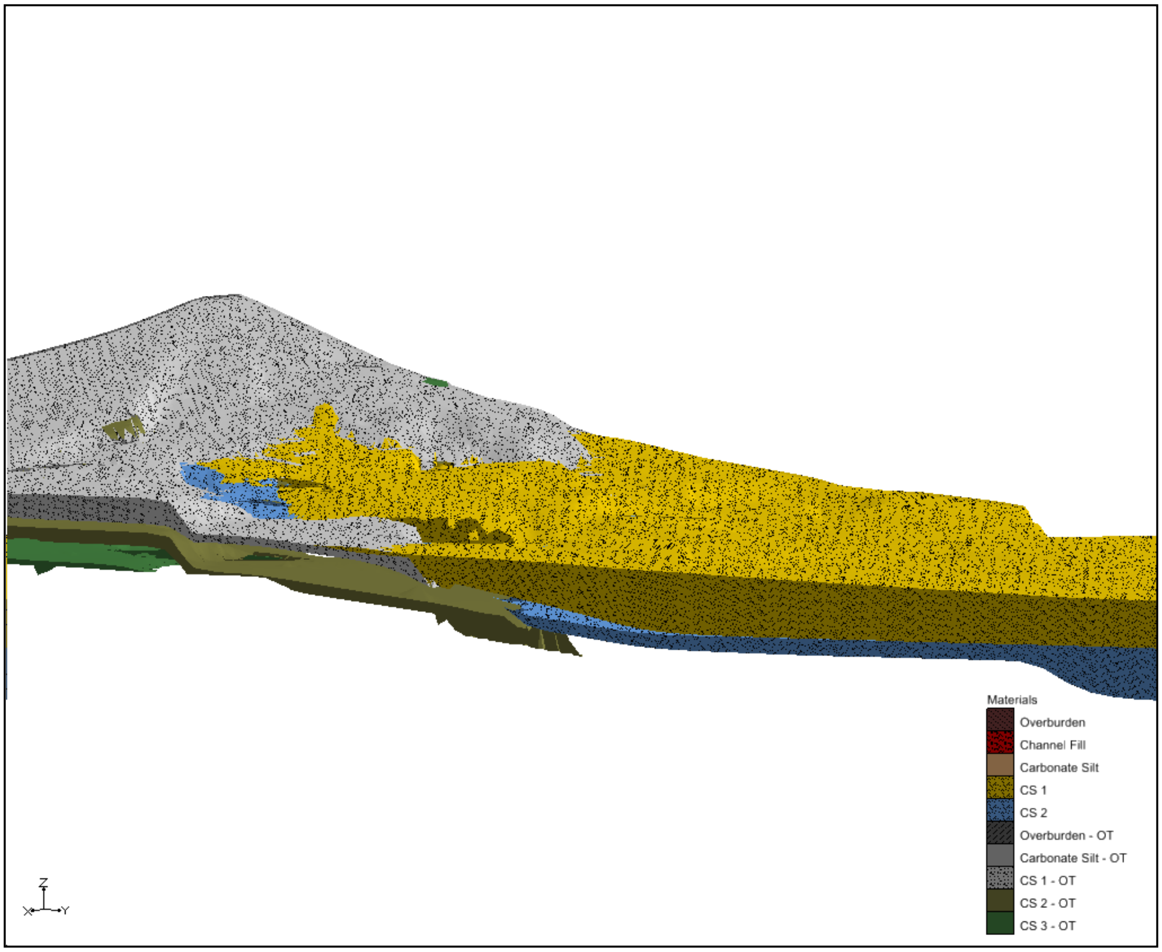

Figure D-4. Oblique view of overlapping carbonate sand aquifers.

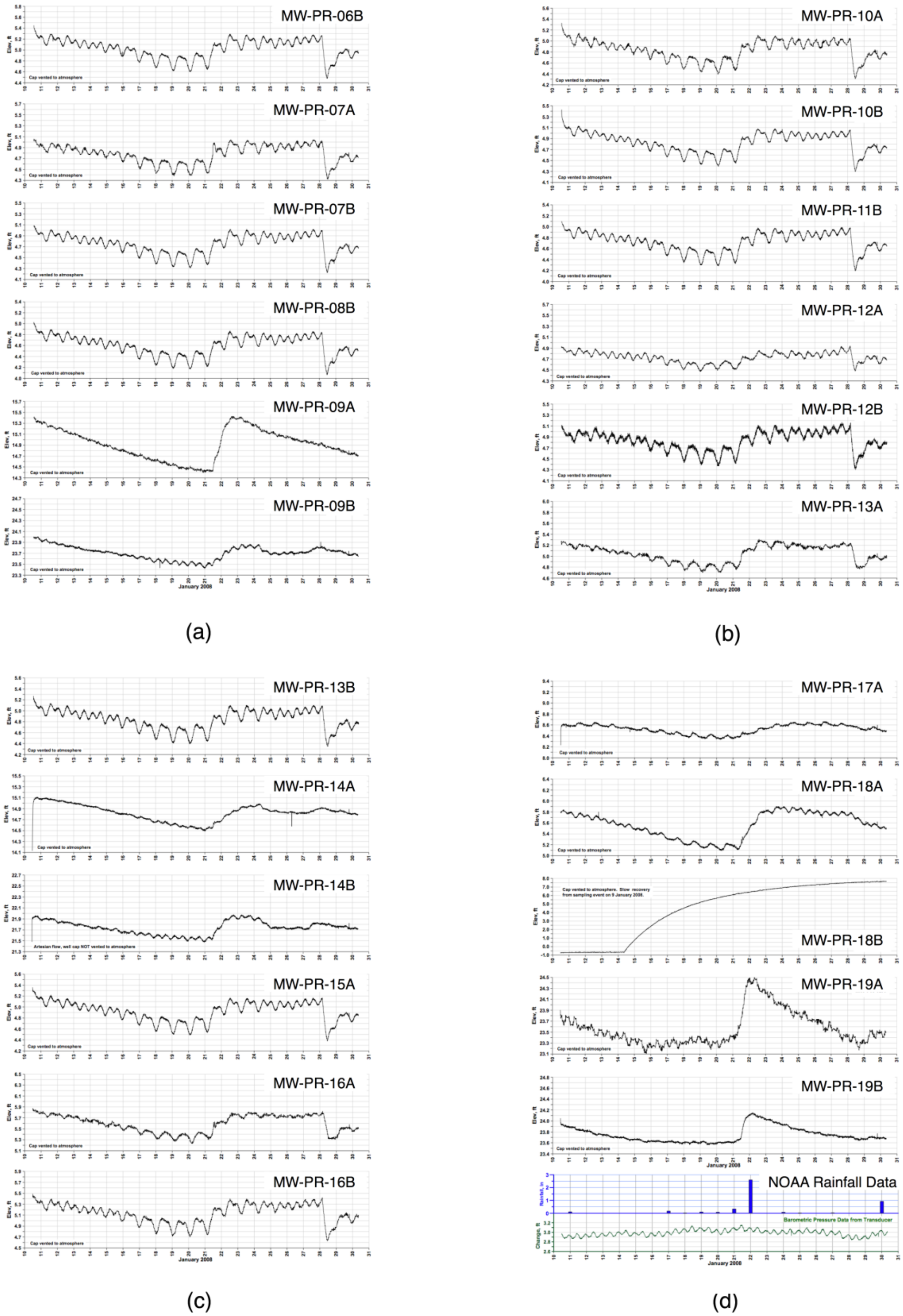

Figure D-5. Rainfall hyetograph and transducer data plots from 23 wells across Fort Buchanan from 10-31 Jan 2008.

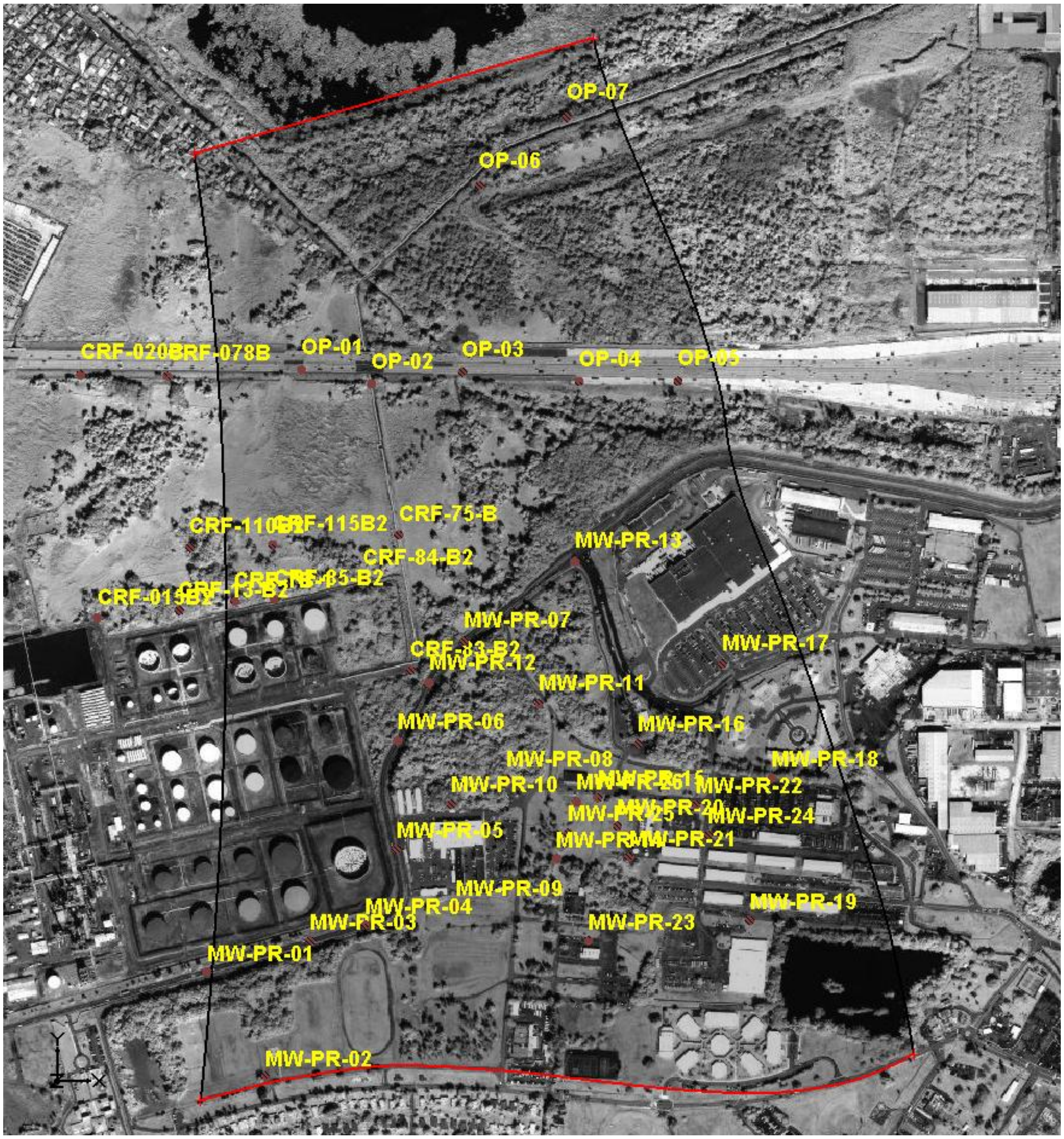

Figure D-6. Model boundaries for Fort Buchanan Northwest Boundary Investigation groundwater flow model.

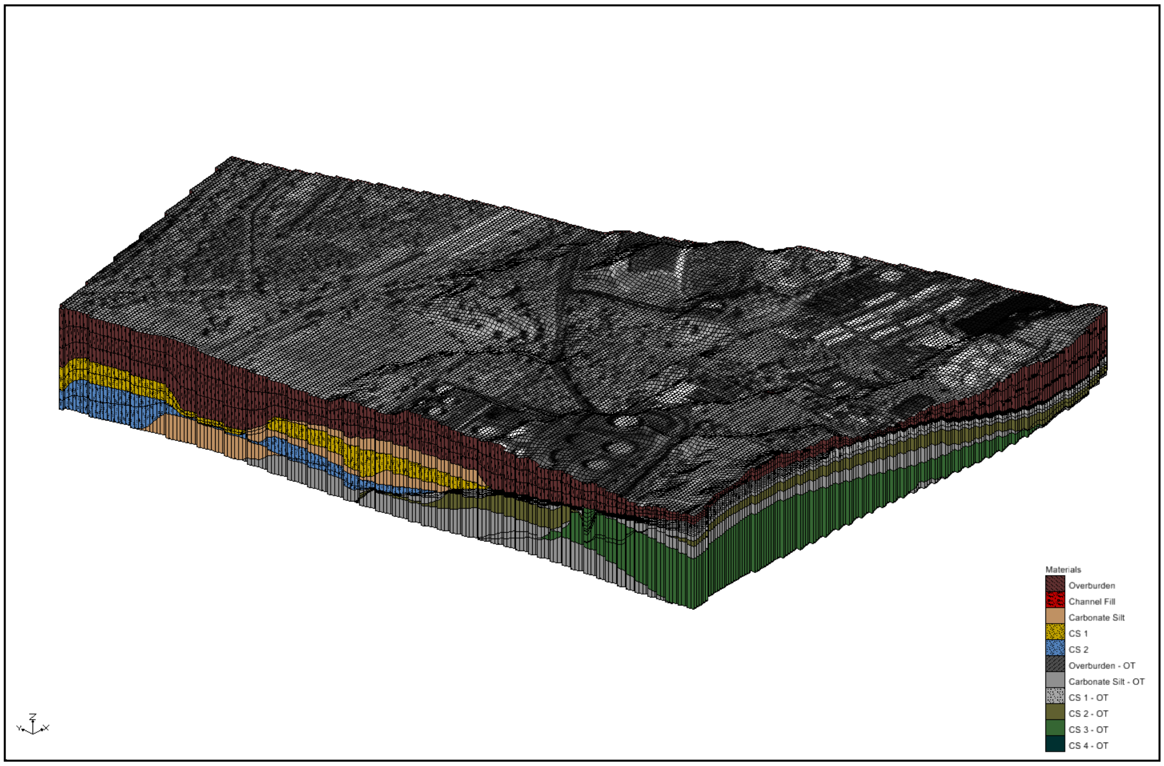

Figure D-7. MODFLOW numerical model grid.

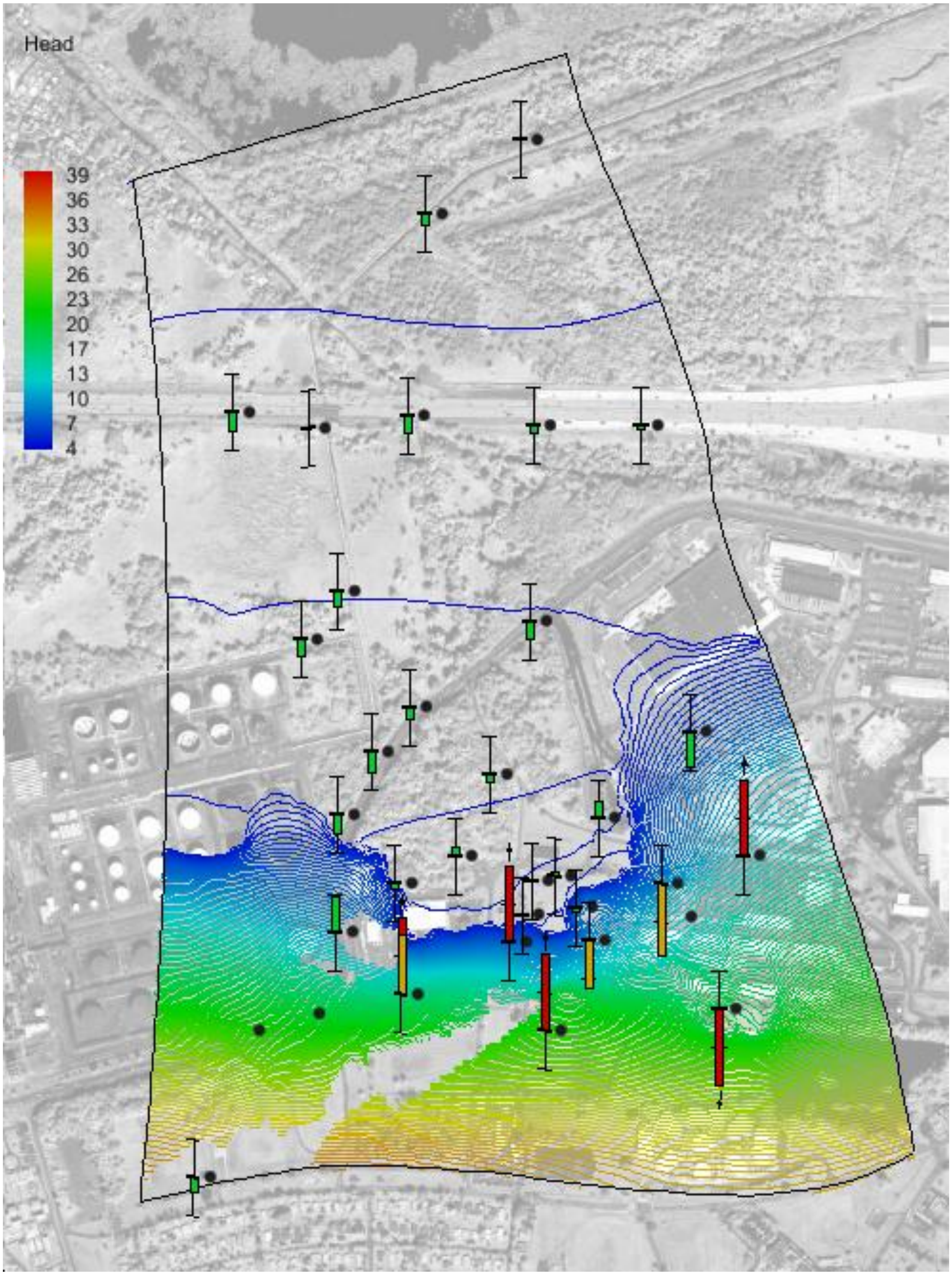

Figure D-8. MODFLOW model groundwater head contours and calibration targets for final calibration results.

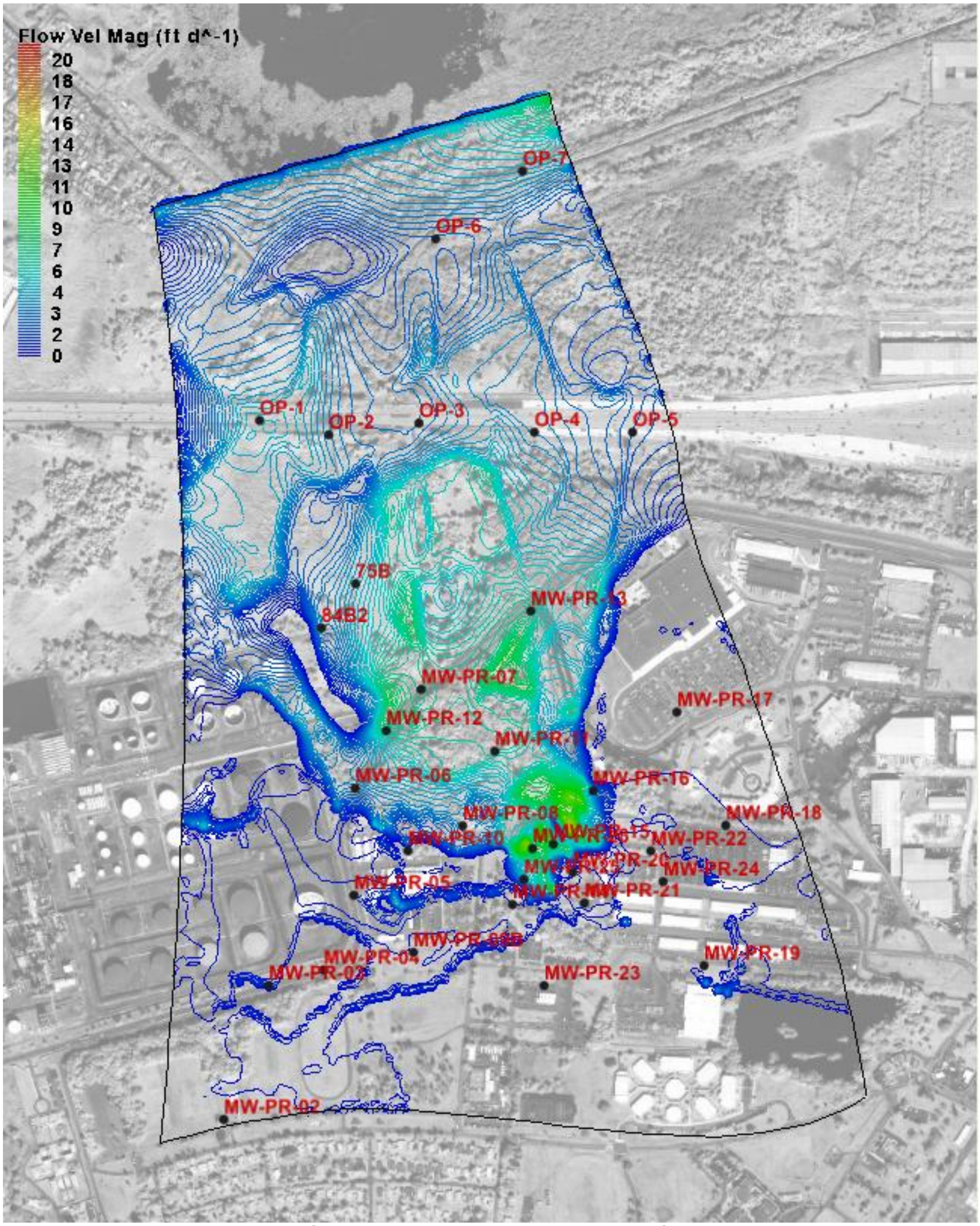

Figure D-9. Contours of model-computed groundwater flow velocities in younger terrace units.

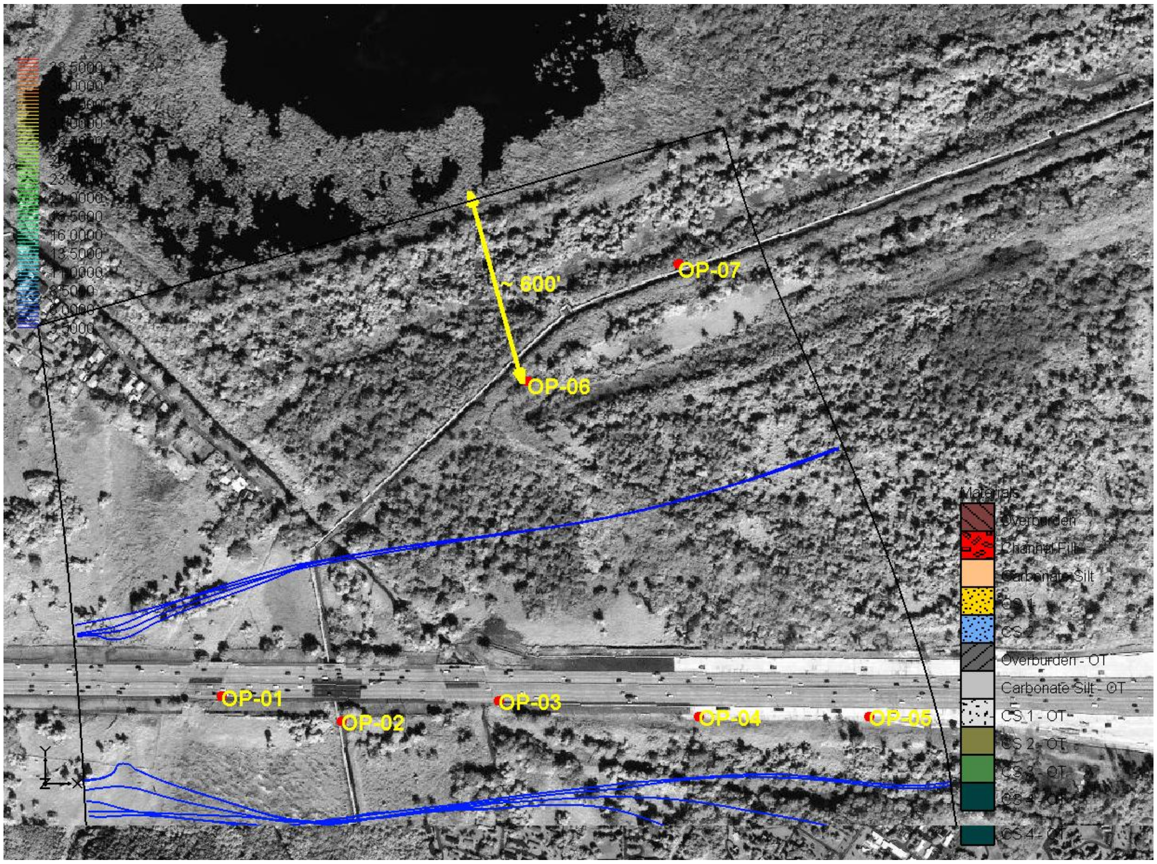

Figure D-10. Distance from OP-6 to surface water body.

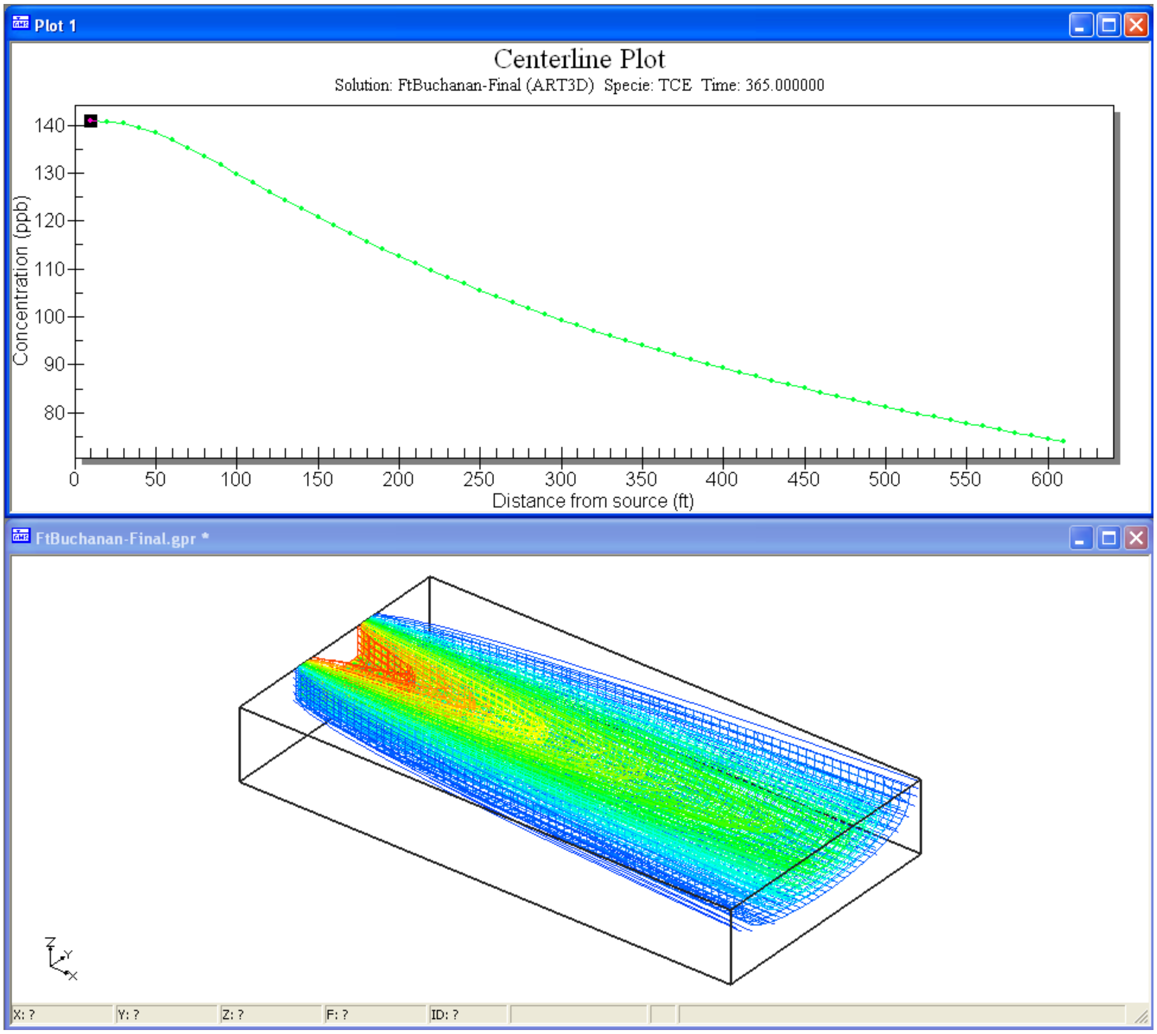

Figure D-11. ART3D transport model results with centerline plot of concentrations (top) and iso-surfaces of concentration (bottom).